

Causes and Effects of Longitudinal Shrinkage and Temperature Stresses on JPCP for Dutch Conditions

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Abstract

In 2010 Houben has published a paper on the modelling of the process of cracking at transverse joints in jointed plain concrete pavements (JPCP). Houben uses equations from the standard Eurocode 2 for the time-dependent concrete properties and considers the thermal deformation and the shrinkage (drying and autogenous) for different design and construction conditions. For properties that are not available in standards, Houben made assumptions based on engineering judgment.

In this present paper the point of departure is the Houben model, and now the assumptions made in his work are studied more in depth. The paper also includes an improvement of the development of the concrete elastic modulus and strength. Accordingly, the objective of this paper is to improve the theoretical background of the assumptions and the determination of the effects of longitudinal shrinkage and temperature stresses on JPCP for Dutch conditions. Concerning one of the most important influencing factors, the relaxation, a new equation is proposed. From both the theoretical and the practical point of view these improvements describe in a better way the causes and effects of longitudinal shrinkage and temperature stresses on JPCP for Dutch conditions.

Introduction

Understanding the effects of the longitudinal shrinkage and temperature stresses in JPCP gives more insight into the effects of e.g. the construction process on the performance of the pavements. For instance, knowing the percentage of cracked joints allows identification of the real length of the slabs in service. It is also possible to obtain an optimal combination of slab length and relative joint depth, as a function of the time of construction and the concrete grade. In addition, knowing (and then controlling) one of the main results of the modelling at early-age, the crack width, it is possible to obtain a better structural and functional behavior of the JPCP. This is because the crack width is related with the load transfer efficiency at the transverse joints and the joint faulting.

Considering the link between the early-age behavior of the concrete and the performance of the JPCPs, rather than to the absolute values one should look to trends with respect to the early-age behavior as these trends are in agreement with field performance.

The point of departure of this paper is the Houben modeling with respect to the cracking of the transverse joints in JPCP. The theoretical background starts showing the factorial of Houben work and highlighting the independent variables studied more in depth in this paper. After that the Dutch conditions are described and

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a comparison of the models used in this work. Then the analysis of the modelling process for the chosen scenarios of evaluation is presented. This section includes a sensitivity analysis and a new approach in the modelling process.

Objective

The objective of this paper is to improve the theoretical background of the causes of longitudinal shrinkage and temperature stresses and the determination of the effects on JPCP for Dutch conditions.

Research Significance

A better explanation of the causes and determination of the effects of the longitudinal shrinkage and temperature stresses in JPCP allows taking better decisions in the design process for a better performance of the pavements.

Theoretical background

Houben modelled the drying and autogenous shrinkage according to the standard (Eurocode 2 2005).

Drying shrinkage. In equation 1, $\varepsilon_{cd}(t)$ is the drying shrinkage; the time t and the start t_s of the drying out are expressed in hours; h_0 is the shape factor. Calculations will be done with $h_0 = 475$ and this results in the value of the coefficient $k_h = 0.706$; $\varepsilon_{cd,0} = 0.000276$ for concrete grade C28/35 in outside air, with a relative humidity of 80%.

$$\varepsilon_{cd}(t) = (t/24 - t_s/24) / \{ (t/24 - t_s/24) + 0.04 * h_0^{1.5} \} * k_h * \varepsilon_{cd,0} \quad (1)$$

Autogenous shrinkage. In equation 2, $\varepsilon_{ca}(t)$ is the autogenous shrinkage; the time t is again expressed in hours; f_{ck} is the characteristic compressive strength.

$$\varepsilon_{ca}(t) = 1 - e^{-0.2 * \sqrt{(t/24)} * 2.5 * (f_{ck} - 10) * 10^{-6}} \quad (2)$$

The point of departure of the present work is the modelling of the transverse cracking at joints in JPCP published by Houben (Houben 2010). Figure 1 shows the factorial of the Houben work with the independent variables (causes). The dependent variables (effects) were the time of occurrence and locations of the cracks, the crack widths and the tensile stress in the middle of the slabs after the cracking process is completed.

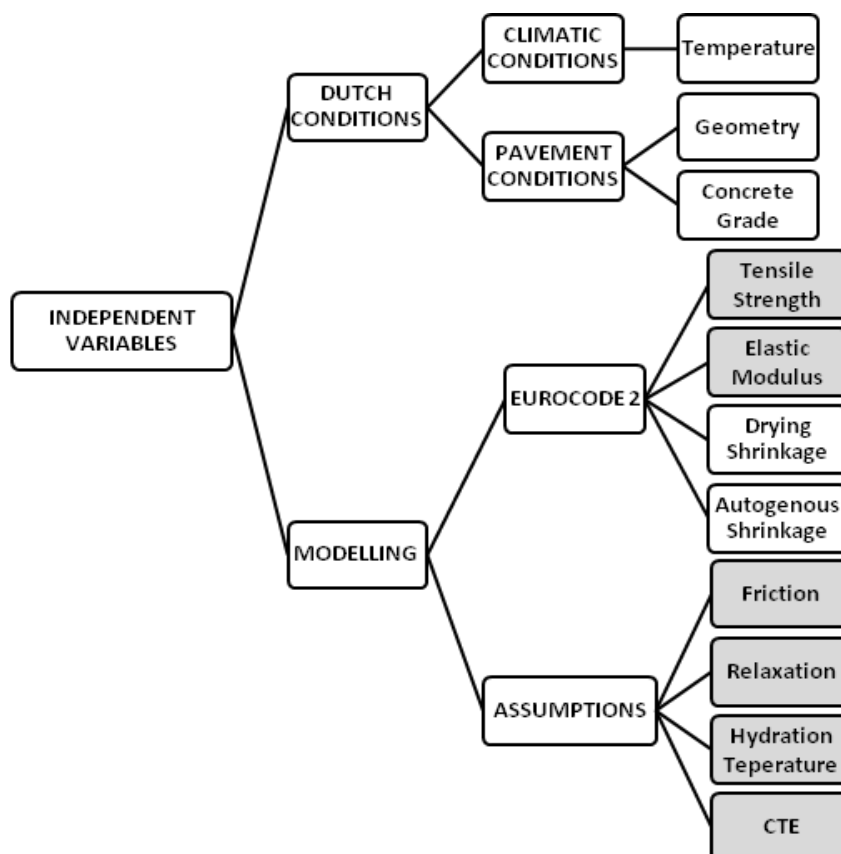


Figure 1. Factorial of the Houben work showing the independent variables (causes).

The figure 1 shows highlighted the independent variables taken into account in this paper for an improvement of the theoretical background. The assumptions of the Houben modelling are based on engineering judgment and they are related with required properties that are not available in standards. In the present work the assumptions made in his work are studied more in depth. Also it includes an improvement of the development of the concrete elastic modulus and strength through the maturity method.

Maturity method. A better modelling of the development of the concrete elastic modulus and strength at early-age is obtained when the concept of degree of hydration or the maturity method is applied. De Schutter has shown that the concept of degree of hydration and the maturity method principally yield the same results and both methods can be recognized as valid tools for modelling the behaviour of early age concrete (De Schutter 2004). The advantage of the maturity method is that it also has a very practical application at the construction process that helps to reach the objectives of the concrete pavement design.

The rate of hydration of cement increases with increasing temperature. Consequently, the mechanical properties of concrete and their development in time are also influenced by the temperature. In fact every combination of temperature and time that yields the same maturity will have the same value of the property.

The Nurse-Saul maturity relationship is the accumulated product of time and temperature. But the Nurse-Saul approach is limited in that it assumes that the rate of strength gain is a linear function. On the other hand, the Arrhenius method takes into account the nonlinearity in the rate of cement hydration. This method expresses a maturity index in terms of an equivalent age (equation 3), which represents the

equivalent duration of curing at the reference temperature that would result in the same value of maturity as the curing period for the given average temperature (FHWA 2005).

$$t_e = \sum \exp\{-(E/R) * [1/273 + T_a] - 1/(273 + T_r)]\} * \Delta t \quad (3)$$

- t_e = equivalent age at reference curing temperature (hours)
 E = activation energy (J/mol)
 R = universal gas constant, 8.3144 J/(mol K)
 T_a = average concrete temperature during time interval Δt (°C)
 T_r = reference temperature (°C)
 Δt = time interval (hours)

Development of the heat of hydration. The hydration of the cement releases heat resulting in temperature increase. This hydration temperature is described by equation 4.

$$T_h = \frac{m_c * Q}{d_c * c_c} \quad (4)$$

- T_h = hydration temperature (°C)
 m_c = mass of the cement per m³ of concrete (kg)
 Q = hydration heat released till time t (kc/kg)
 d_c = density of concrete (kg/m³)
 c_c = specific heat of the concrete (kc/kg/°C)

The hydration heat released can be calculated using *HYMOSTRUC* software (Van Breugel 1991).

Relaxation factor. The experimental data on stress relaxation at early ages are very limited. Theoretical expressions and relationships with the development of creep are commonly used. But Morimoto and Koyanagi performed laboratory tests, at room temperature, and they found the following empirical equation for the relaxation as a function of time (Morimoto and Koyanagi 1995).

$$R = \frac{0.32 + 0.85 * t}{0.32 + t} \quad (5)$$

Development of the coefficient of thermal expansion. In general the standards and recommendations include a constant value for the coefficient of thermal expansion (CTE) of hardened concrete. For instance, in the Eurocode 2 the CTE-value $10 * 10^{-6} \text{ } ^\circ\text{C}^{-1}$ is advised for concrete (Eurocode 2 2005). However, the CTE is not necessarily constant in fresh concrete. The CTE is high in the first hours and it drops rapidly to a minimum value at $t_0 = 12\text{-}14$ hours after mixing. Beyond this minimum point the CTE increases gradually.

The “time zero” (t_0) is the time when strength and stiffness of concrete is defined to be zero, which means that the deformations occurring before this “time zero” can be ignored for stress calculation purposes, since they do not result in stresses (Cusson and Hoogeveen 2007).

The development of the CTE can be expressed by the equation 6 (Atrushi 2003).

$$CTE(t_e) = CTE(0) + [CTE(28) - CTE(0)] \left\{ \exp \left[s_{CTE} \left(1 - \sqrt{\frac{28}{t_e - t_0}} \right) \right] \right\}^{n_{CTE}} \quad (6)$$

$CTE(0)$ = the start-value at t_0 ($^{\circ}\text{C}^{-1}$)
 $CTE(28)$ = the CTE-value at 28 days ($^{\circ}\text{C}^{-1}$)
 s_{CTE} and n_{CTE} = curve-fitting parameters
 t_e = the equivalent time (hours)

Friction with the base. Zhang and Li have presented an analytical model for the prediction of the shrinkage-induced stresses and displacements in concrete pavements due to the restraint of the supporting base. The following is the governing equilibrium equation (Zhang and Li 2001).

$$\frac{d^2u}{dx^2} - \frac{\tau}{E * h} = 0 \quad (7)$$

τ = slab-base interfacial friction (MPa)
 u = average displacement through the JPCP slab thickness (mm)
 E = elastic modulus of concrete (MPa)
 h = height of the slab (mm)

Application to JPCP in Dutch conditions

The typical Dutch condition for JPCP includes enough length to consider the pavement fixed at the beginning and at the end, i.e. no deformations are allowed there. The Houben modelling of the friction with the base considers this situation through the so called breathing length (Houben 2010), but the Zhang and Li modelling introduces the friction from the beginning and from the end (Zhang and Li 2001). This is representative for pavements of small length, such as streets. Accordingly, in this work the Houben model remains used.

Dutch climatic conditions mean that the amplitude of the average daily temperature of the concrete pavement (T_{ampyear}) has been taken as 10°C , where T_{ampyear} is described by means of a sine-function with its maximum at August 1. The amplitude of the daily temperature of the concrete pavement (T_{ampday}) has been taken as 5°C , and also T_{ampday} is described by means of a sine-function that reaches its maximum at 4 PM. The climate-dependent temperature T_3 of the plain concrete pavement is thus taken from (Houben 2010).

Comparison of models

Table 1 shows a summary of the variables in Houben model (Houben 2010) and the present work. E_c is the elastic modulus of concrete.

Table 1. Comparison of models.

Independent variables	Houben	Alternative approach
Strength and elastic modulus	Eurocode 2	Eurocode 2 + Equation 1
Hydration temperature	$T_h(t) = t^2 * e^{-0.27*t}$	Equation 2
Stress Relaxation	$R(t) = e^{-0.0003*t}$	Equation. 3
Coefficient of thermal expansion	$CTE(t) = 3.095 * 10^{-10} * E_c(t)$	Equation. 4

Scenarios of evaluation

The objective of this present work is to improve the modelling of longitudinal shrinkage and temperature stresses and the determination of the effects on JPCP for Dutch conditions. For showing the improvements in a better way, focusing on the comparison between the modelling of Houben and the alternative approach, a typical scenario of evaluation was chosen (table 2).

Table 2. Parameters of the scenarios of evaluation

Parameter	Data
Transverse joint spacing	4.5 m
Concrete grade	C28/35
Joint depth	30%
Day of construction	August 1 st , 4 PM / November 1 st , 10 AM

In 2010 Houben published a complete analysis for different concrete grades, joint depths, slab lengths and different days of construction. According to Houben, and from the point of view of the effects on the pavement, the most critical situations for JPCP in Dutch climatic conditions are when the pavement is constructed at August 1st, 4 PM (highest concrete temperature within a year) and November 1st, 10 AM (Houben 2010).

Summary of Houben results

The figures 2, 3, 4 and 5 present a summary of the results of Houben modelling for the scenarios of evaluation selected in this present work.

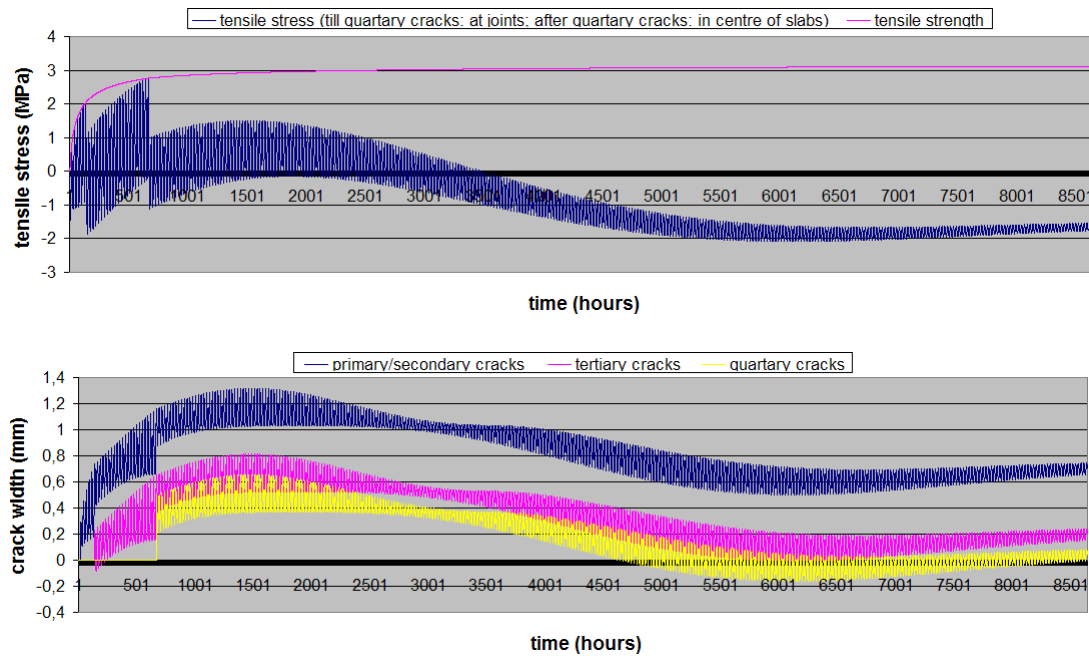


Figure 2. Maximum tensile stress and crack widths for construction at November 1st, 10 AM (Houben 2010).

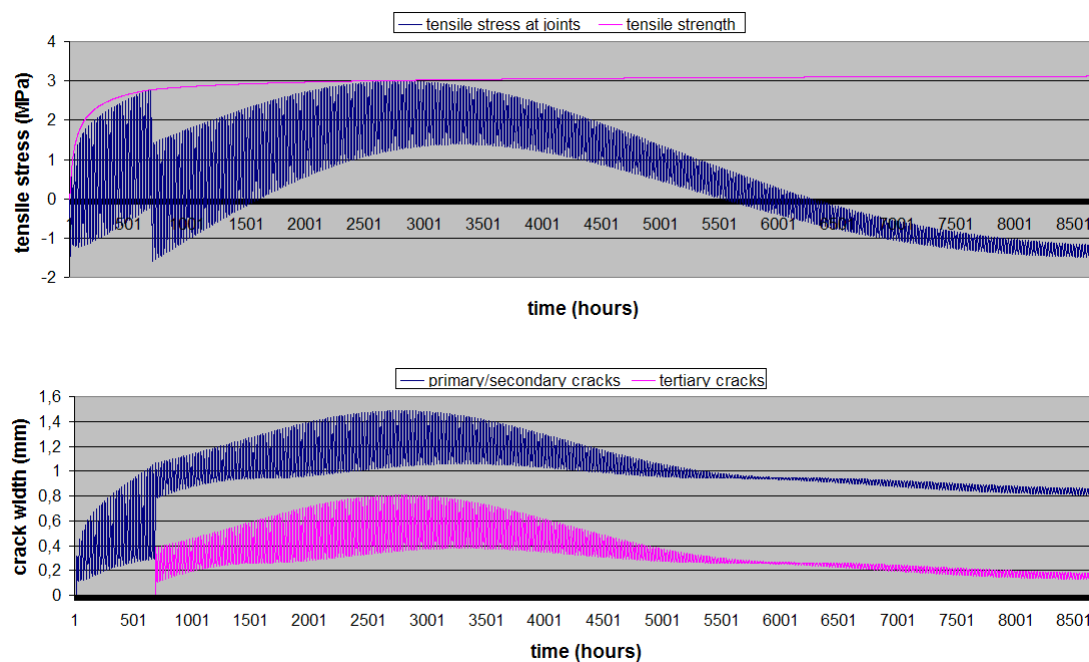


Figure 3. Maximum tensile stress and crack widths for construction at August 1st, 4 PM (Houben 2010).

Analysis of the modelling process

The alternative approach for the modelling of the independent variables improves the theoretical background, but the most significant changes for the behaviour of the pavement result from the stress relaxation and the introduction of the maturity in the calculation of the concrete properties. For that reason these two improvements are considered in a sensitivity analysis.

In figure 4 the hourly cyclic variation of the tensile strength can be observed, because the maturity introduces the concrete temperature during the time interval Δt for the calculation of the strength.

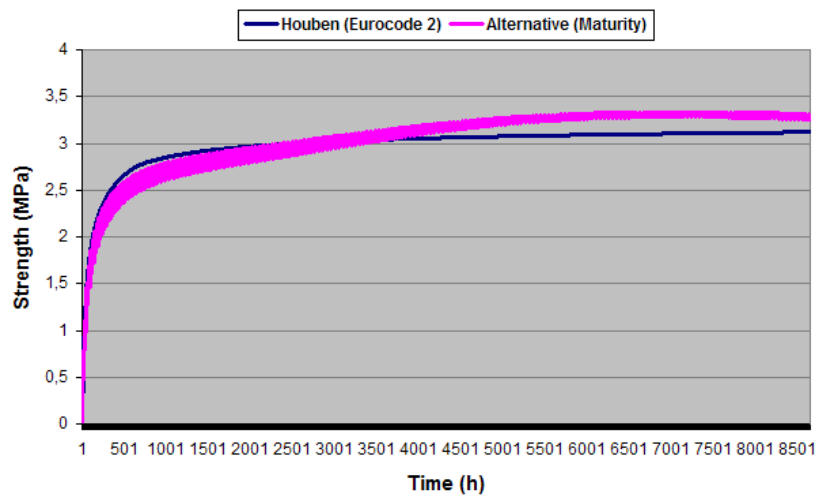


Figure 4. Tensile strength according to Houben and the alternative approach.

Sensitivity analysis for the maturity method. The modelling was made for the maturity method under *ceteris paribus* condition.

The figures 5 and 6 show the tensile stresses and the crack widths, respectively, with the introduction of the maturity in the calculation of the concrete properties. In the figures 5 and 6 the time of construction is November 1st, 10 AM.

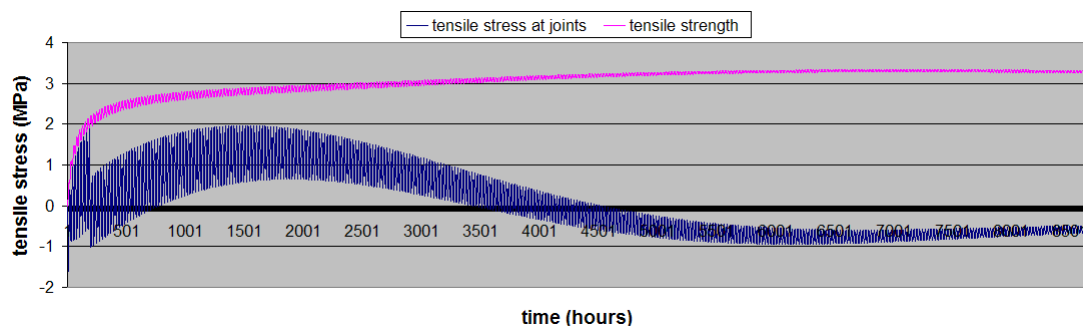


Figure 5. Maximum tensile stress according to the alternative approach (maturity).

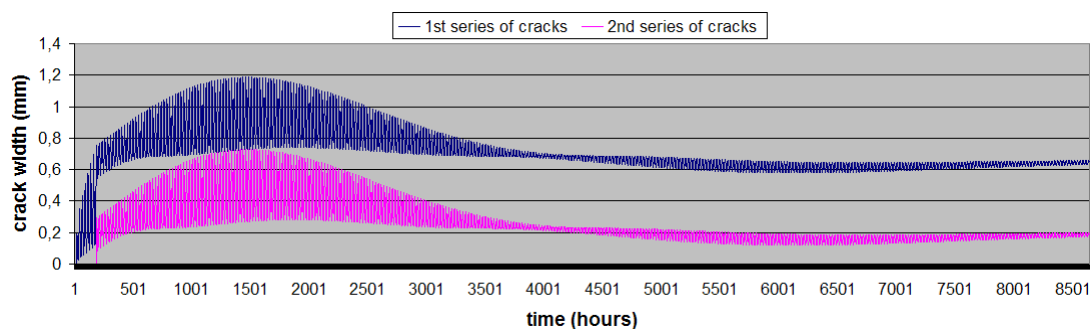


Figure 6. Crack widths according to the alternative approach (maturity).

The table 3 shows that the introduction of the maturity in the modelling does not change significantly the trends of the results.

Table 3. Comparison of the results with the maturity method.

Dependent variables	Houben	Alternative approach
Joints cracked (%)	100	100
Risk of cracks in the slab (ratio)	0.51	0.71
Maximum crack width (mm)	1.31	1.19
Average width of 1 st series of cracks after 1 year (mm)	0.70	0.65

Sensitivity analysis for the relaxation factor. The modelling was made for the relaxation factor under *ceteris paribus* condition.

The figures 7 and 8 show the crack widths with the alternative approach of the relaxation factor (Morimoto and Koyanagi 1995).

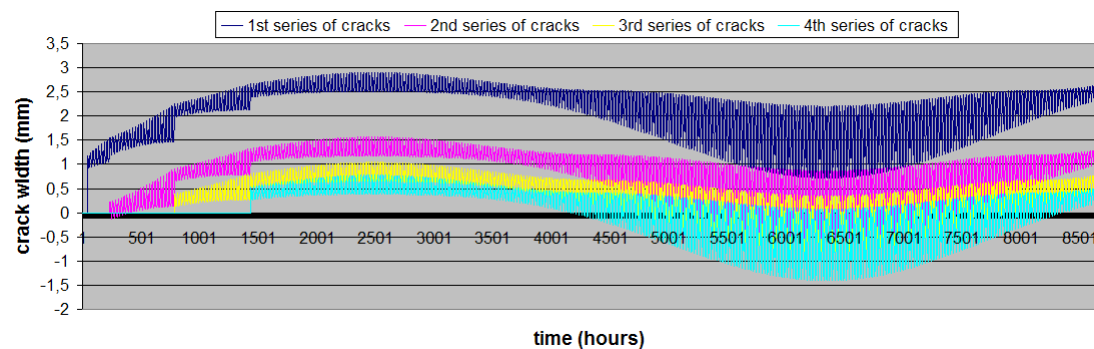


Figure 7. Crack widths according to the alternative approach
Day of construction, November 1st, 10 AM.

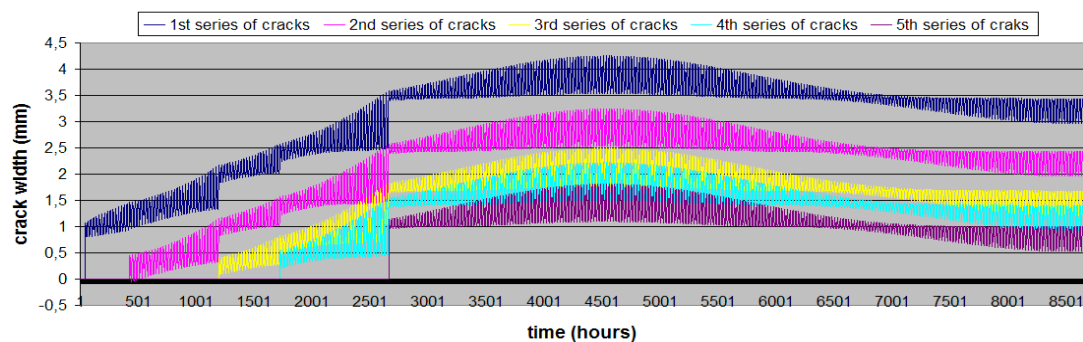


Figure 8. Crack widths according to the alternative approach
Day of construction, August 1st, 4 PM.

The table 4 shows a summary of the crack widths obtained with the alternative approach and with the Houben modelling of the relaxation factor. According to experience and preliminary field measurements in Belgium and Chile, in similar climatic conditions to the Netherlands, the crack width seems to be greater than the Houben model indicates but smaller than the result of the alternative approach.

Table 4. Comparison of the crack widths for different relaxation factor.

Day of Construction	Model	Maximum crack width (mm)	Average width of 1 st series of cracks after 1 year (mm)
November 1 st 10 AM	Houben	1.31	0.70
	Alternative approach	2.90	2.52
August 1 st 4 PM	Houben	1.48	0.84
	Alternative approach	4.25	3.23

But not only the crack widths seem too high, but also the tensile stresses. For instance, the figure 9 shows the tensile stress, calculated with the alternative approach, for the case of a JPCP constructed at August 1st, 4 PM, i.e. at the hottest moment of the year.

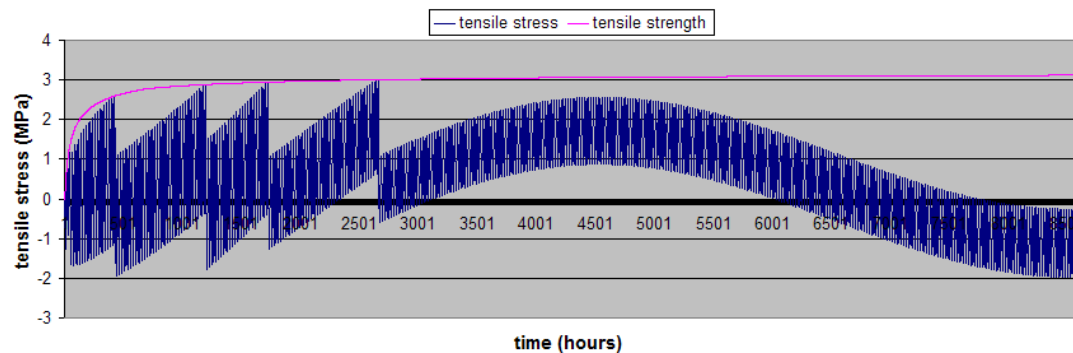


Figure 9. Maximum tensile stress according to the alternative approach
Day of construction, August 1st, 4 PM.

In this case not only 100% of the joints are cracked, but the alternative approach also leads to cracks in the slabs, so in between the transverse joints. This is not observed in practice and means that in the alternative approach the relaxation is too small.

On the other hand, there are relaxation models with a fast fall at the beginning, up to 50% relaxation (Van der Ham et al. 2009). However, the application of this model results in a low percentage of joints cracked and very small crack widths and that is also not observed on JPCP in practice.

Furthermore, one has also to realize that a JPCP is opened to traffic 2 weeks to some months after construction. The structural design of JPCP is done considering traffic load stresses and temperature gradient stresses, but omitting shrinkage stresses. This indicates that the shrinkage stresses after some months cannot be very large.

New approach. Taking into account all the theoretical and practical reasons mentioned previously, a new equation for the relaxation factor, as a function of time, is proposed (equation 8 and figure 10).

$$R = 0.8265 * e^{-8*10^{-5}*t} \quad (8)$$

The figures 11 and 12 present the tensile stress and the crack widths, respectively, with the new approach of the relaxation factor. The table 3 shows, as a

summary, the results obtained with the different models. Both the figures and the table correspond to the construction at November 1st, 10 AM.

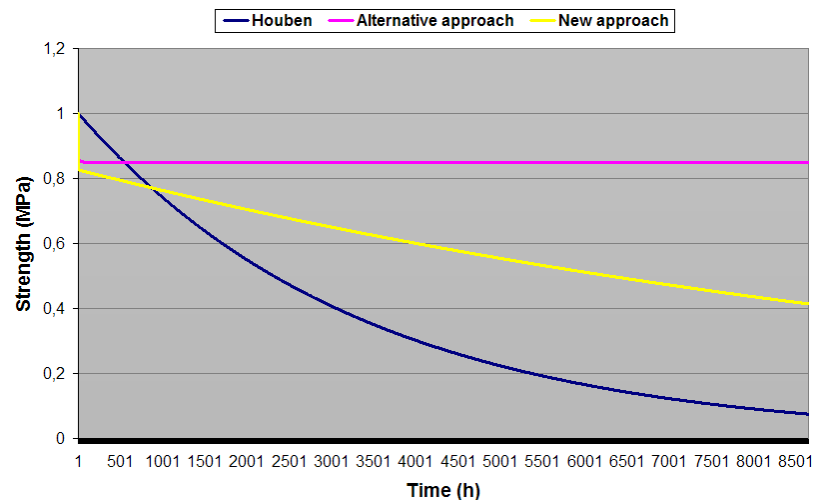


Figure 10. Different stress relaxation factors.

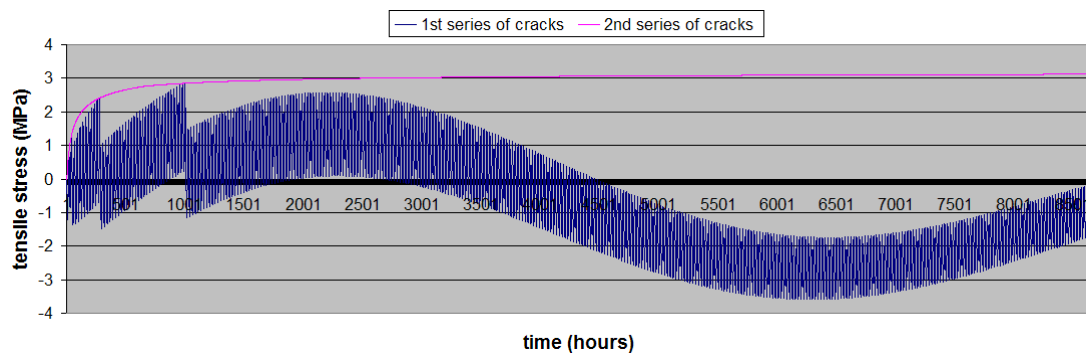


Figure 11. Maximum tensile stress according to the new approach of the relaxation factor.

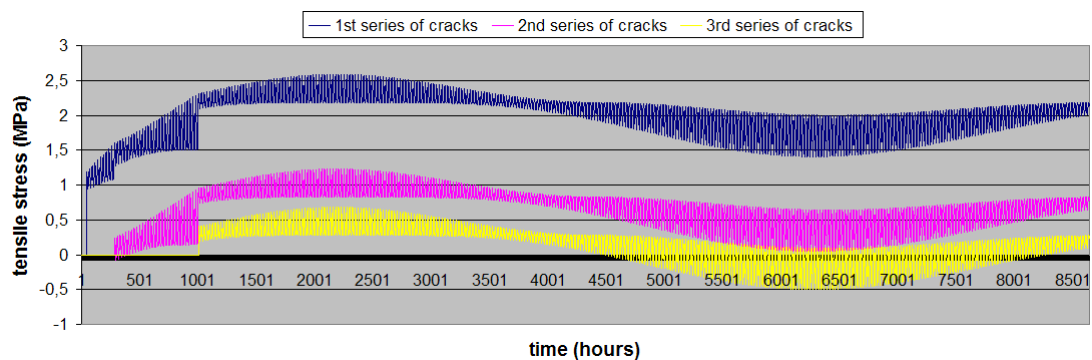


Figure 12. Crack widths according to the new approach of the relaxation factor.

Table 5. Results of the different models.

Dependent variables	Houben	Alternative approach	New approach
Joints cracked (%)	100	100	55
Risk of cracks in the slab (ratio)	0.51	0.58	very small
Maximum crack width (mm)	1.31	2.90	2.56
Average width of 1 st series of cracks after 1 year (mm)	0.70	2.52	2.16

The trend of the results according to the new approach is between the two previous models. Due to the smaller stress relaxation the new approach yields higher maximum stresses, larger seasonal and daily stress amplitudes and larger widths of the cracked transverse joints than the Houben model. It is expected that this equation can be validated through ongoing field measurements on JPCPs in Belgium and Chile.

Conclusions

In this work the theoretical background for the modelling of the causes of longitudinal shrinkage and temperature stresses made in the Houben work is improved.

The trends of the effects on the pavement did not change significantly, with the exception of the alternative stress relaxation. In this case high values of crack widths and the possibility of slabs cracked at medium term were found, because of the almost constant small relaxation and the addition of the effect of the traffic loads and temperature gradients. Both, the width of the cracks and the possibility of cracked slabs, are not in agreement with the reality of JPCP for Dutch conditions. Additionally, the structural design of JPCP is done considering traffic load stresses and temperature gradient stresses, but omitting shrinkage stresses. This indicates that the shrinkage stresses after some months cannot be very large.

According to experience and preliminary field measurements in Belgium and Chile, in similar climatic conditions as the Netherlands, an equation for the relaxation factor is proposed. The trend of the results seems in agreement with reality but needs to be validated.

A reliable modelling of the causes and effects of the longitudinal shrinkage and temperature stresses on JPCP allows, *a priori*, taking decisions that will positively affect the behaviour of in-service JPCPs.

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